Scattering of Polarized Neutrons by Protons

In spite of many attempts, it has not been possible so far to develop a theory of nuclear forces which accounts in a satisfactory way for all the properties of even the simplest system, a neutron and a proton. An alternative procedure might, therefore, be attempted, namely, to obtain the interaction potential empirically from the various observed properties like the binding energy, quadrupole moment, magnetic moment of the deuteron and the scattering cross-section. The latter seems particularly useful for this purpose, as there exist general reciprocal quantum mechanical relations between the differential scattering cross-section $d\sigma$ and the interaction potential; $d\sigma$ is expressed in terms of certain phase shifts η_l, ($l = 0, 1, 2, \ldots$), suffered by the partial waves of different orbital angular momentum l due to the interaction between the two particles. For spinless particles, a knowledge of $d\sigma$ (as a function of the angle of scattering θ) determines all the phase shifts η_l and *vice versa*, and a knowledge of the phase shift η_l (as a function of energy) for a given l-state determines the interaction potential for that l-state and *vice versa*. However, the fact that the neutron–proton system splits into the singlet and triplet states (with different interactions) makes the determination of the phase-shifts from a knowledge of $d\sigma(\theta)$ alone impossible.

It is the purpose of this note to point out that this difficulty can be overcome by utilizing an additional property, namely, the partial depolarization of a polarized beam of neutrons on scattering by an unpolarized proton gas. This partial depolarization is due to the spin dependence of the interaction potential; for example, if the triplet interaction were zero, then the scattered neutrons would be completely depolarized. The result of depolarization measurements can be expressed in terms of a depolarization factor P, defined as the difference between the absolute probabilities that the spins of scattered neutrons point parallel or antiparallel to the spin direction of the incident neutrons.

Now if the interaction potential were spherically symmetrical then it can be shown that from a knowledge of the angular distribution of scattering cross-section and of P, all the phase-shifts both for triplet and singlet states could be uniquely determined and thus the interaction potentials themselves could be obtained. From the existence of the quadrupole moment of the deuteron, it is known, however, that the neutron–proton interaction is not spherically symmetrical; usually one assumes the interaction potential as a sum of a spherically symmetrical term and a non-central term (which is a function of the angles which the spin directions of the two particles make with the line joining them), the latter being often denoted as tensor interaction. In the presence of the latter, the above analysis for utilizing the experimental observations to determine the phase-shifts and the interaction potential will become more involved than in the previous case. On the other hand, a qualitatively new feature appears in an *azimuthal* dependence of the depolarization P, provided the spin direction of the incident neutrons makes a finite angle α with the incident direction; the azimuthal dependence being greatest when $\alpha = \pi/2$. It is possible to give the expected order of magnitude of the azimuthal variation of P by making use of an interaction potential which gives the correct quadrupole moment and binding energy of the deuteron; for the case $\alpha = \pi/2$, and at $\theta = \pi/2$, the maximum azimuthal variation in P, namely, $P_{\varphi=0} - P_{\varphi=\pi/2}$ ($\varphi = 0$ gives the plane containing the directions of motion and of spin of incident neutrons), is about $\frac{1}{2}$ per cent and 40 per cent for incident neutrons of energies 1 MeV. and 100 MeV. respectively. It thus follows that detection of the azimuthal dependence of the depolarization should permit a determination of details of the non-central interaction between a neutron and a proton.

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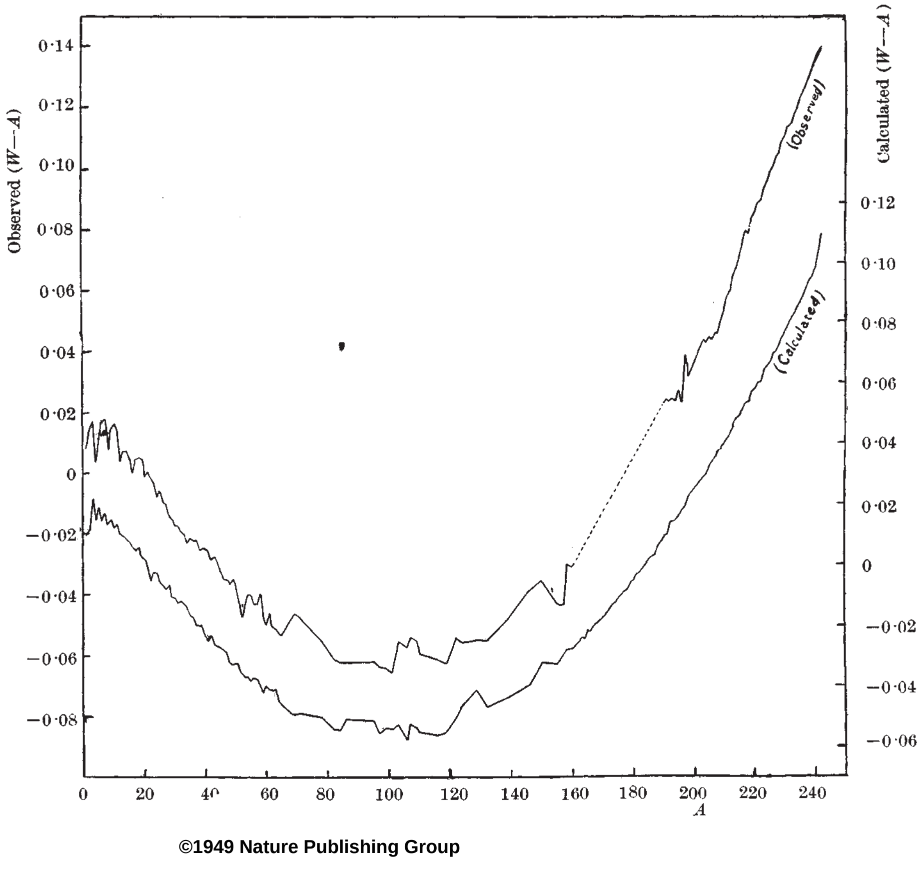
Mass-Defect Curves

In the accompanying graph, giving $(W - A)$ plotted against A, where W is the atomic weight and



A the mass number, two curves, marked 'observed' and 'calculated', are shown, and the latter is discussed in the letter below. The 'observed' curve is based on the empirical data given by Rosenfeld at the end of his book on "Nuclear Forces". The points corresponding to stable nuclei have been joined together by straight lines, and other points have been omitted. There is a gap in the data from $A = 160$ to $A = 190$, indicated by the dotted line.

The periodicity of 4, for the lighter nuclei, is brought out very clearly in the graph. This is especially apparent for $A \leqslant 24$. The heavy naturally radioactive group has been included.

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FROM theoretical considerations, the average binding energy per nucleon can be put in the form[1]

$$\varepsilon = -\varepsilon_1 \left[1 - \gamma \left(\frac{A - 2Z}{A}\right)^2\right] + 4\pi r_0^2 o A^{-1/3} + \frac{3}{5}\frac{c^2}{r_0} Z^2 A^{-4/3}. \qquad (1)$$

Numerical values of the parameters ε_1, γ, o and r_0 have been estimated empirically by Mattauch and Flugge[2]:

$$\begin{aligned} \varepsilon_1 &= 14\cdot66 \text{ MeV.}, \quad \gamma = 1\cdot40 \\ 4\pi r_0^2 o &= 15\cdot4 \text{ MeV.}, \quad r_0 = 1\cdot42 \times 10^{-13} \text{ cm.} \end{aligned} \qquad (2)$$

Since for a nucleus containing N neutrons and Z protons the average binding energy takes the form

$$\varepsilon = \frac{W - Zm_p - Nm_n}{A}, \qquad (3)$$

where m_p and m_n are the atomic weights of a proton and neutron, it is possible to calculate $(W - A)$ from (1), (2) and (3) and to compare the results with the experimental data.

In the preceding note, Prof. Mosharrafa's 'observed' curve is drawn just above the 'calculated' curve for comparison (the two curves are drawn with the same abscissa but with a difference in ordinates of 0·03 mass units).

Although the curve based on the calculated values is of the right shape, the following points are to be observed: (a) the periodicity of four which is clearly brought out for $A \leqslant 24$ in the empirical curve is not shown; and (b) the calculated curve rises less steeply than the empirical one at the end, giving lower values for $(W - A)$.

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[1] Rosenfeld, "Nuclear Forces", 24 (1948).
[2] Mattauch, J., and Flugge, S., "Kernphysikalische Tabellen", 91 (1941).

Inelastic Scattering of Deuterons

WE have recently performed experiments which show that deuterons are scattered inelastically by aluminium and magnesium targets. Such inelastic scattering is well known for protons, but has not hitherto been observed with deuterons.

The apparatus used in these experiments was substantially that described by Rhoderick[1]. The maximum energy of the deuterons available from the cyclotron was 6·7 MeV., and this could be reduced to less than 5 MeV. by placing aluminium foils in the scattering chamber in the path of the incident beam.

In general, the energy spectrum of the particles scattered at a given angle is complex. There are many groups of singly charged particles with ranges both longer and shorter than the range of the elastically scattered deuterons. Most of these are presumably to be attributed to protons formed in (d,p) reactions. In addition, at small ranges there are doubly charged particles which we believe to be alpha-particles formed in (d,α) reactions. As yet, we have not analysed all these groups in detail.

However, with both targets, but particularly with magnesium, certain groups are prominent because of their greater intensities. It is these which we believe to consist of deuterons which have suffered inelastic collisions.

If we calculate the Q value (that is, the excitation energy of the target nucleus) for one of these groups, on the assumption that it consists of deuterons, we obtain a value in very good agreement with that deduced from the inelastic scattering of protons. This is shown in the accompanying table.

	Excitation energy of nucleus (MeV.) Proton scattering	Deuteron scattering
Al^{27}	0·88	0·85
	2·15	2·13
Mg(? Mg^{24})	1·36	1·36

The values we have given for proton scattering are those given by Rhoderick, the 0·88 MeV. in aluminium being the average of his 0·97 and 0·80 MeV. In general, these agree reasonably well with those of other workers. But we regard them as the most satisfactory for comparison with the deuteron figures, since they were obtained with the same apparatus, and many systematic errors will therefore be common to the two sets of data.

Since the particles concerned are singly charged, it is extremely probable either that the above interpretation is correct *or* that they are protons formed in (d,p) reactions. In the latter case the agreement shown in the above table would be fortuitous. However, it is possible to decide between these two hypotheses by a detailed study of the variation of energy (range) of the scattered particles with the energy of the incident deuterons and the angle of scattering. This variation will be different for deuterons and protons formed in (d,d) and (d,p) reactions respectively.

We have made the necessary measurements for the groups corresponding to the 0·88 MeV. level in aluminium and the 1·36 MeV. level in magnesium. In both cases our results agree with the groups of particles being deuterons and disagree with them being protons.

We quote as an example some of the results obtained with magnesium. Measurements were made at seven values of the energy of the incident deuterons. These energies lie between 4·96 MeV. and 6·65 MeV. The Q values calculated, assuming the particles to be deuterons, are scattered about a mean value of 1·36 MeV. with a standard deviation of 0·04 MeV. The extreme values are 1·30 and 1·42 MeV., so that the extreme variation from the mean is only 1·5 × (standard deviation). On the other hand, if we